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## NOISE SUPPRESSORS FOR JET ENGINES

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THESE SUPPRESSORS WERE CAREFULLY STUDIED TO DETERMINE NOISE CHARACTERISTICS, THRUST LOSS, AND DRAG.

# Noise Suppressors for Jet Engines

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THE noise problems which have plagued aviation from its very inception have grown steadily worse over the years. The noise nuisance created by current aircraft in communities surrounding airports has reached the point where public protests have resulted in considerable legislation and litigation. The increased noise potential which was expected to accompany the advent of the jet transport is now here. Public acceptance of these new airplanes depends upon the use of adequate jet noise suppression devices.

For the past five or so years, a great deal of effort has gone into research and development aimed at decreasing the noise problem associated with the jet transport. As long ago as 1953 it was felt that a noise reduction of about 15 db would be required to make the jet transport comparable to propeller driven airplanes.

Research into the problem of jet noise and the means for its reduction has many aspects. At the NACA our first approach was to find the source of the noise. Figure 1 shows a schematic of a turbojet engine and the various sources of noise are classified.

Noise sources are the inlet, the exhaust, and the engine shell. Inlet noise is created internally inside the engine and radiates outward from the inlet. Such a noise, for example, is the compressor whine, which results from the rapidly rotating compressor blades. The radiated noise from the engine shell results from vibration of the shell or from internal noises which radiate outward through the shell. The exhaust noise includes internal noise which is radiated outward through the tailpipe and the noise created by the turbulent mixing of the jet with the surrounding atmosphere. For the

cases of interest, the turbulent mixing noise is the real culprit. The turbulent mixing process creates very intense fluctuations of velocity which result in large pressure waves which propagate outward and are the real source of noise.

Figure 2 shows the means used to identify this mixing process as the noise source. It shows a plot of the sound power radiated from small airjets and several full-scale engines. The sound power is plotted against a parameter, which is called the Lighthill parameter. This parameter was derived by M. J. Lighthill in England and describes the sound power radiated by a moving field of turbulence. Lighthill's work has been extended and amplified by many workers in the field. This particular form of the parameter applies only to simple circular airjets of exit area  $A$  and issuing into a quiescent atmosphere with a jet velocity  $V$ . The

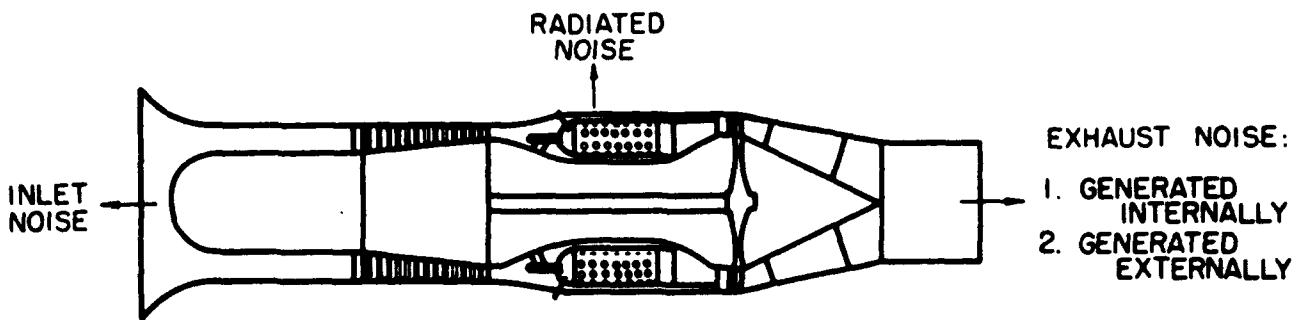


FIG. 1. ENGINE NOISE IS CLASSIFIED BY SOURCE INTO INLET NOISE, NOISE RADIATED FROM ENGINE SHELL, AND EXHAUST NOISE.

atmosphere is described by its density  $\rho_0$  and the speed of sound in the atmosphere  $a_0$ . The results on the figure show that all of the data fit along a single line. Notice that the scales are both log scales, i.e., equal distances correspond to equal ratios of the variable. The slope of the line is such that a change in the Lighthill parameter by a factor of 10 results in a change in the sound power by a factor of 10. This, in itself, is excellent verification of the relationship proposed by Lighthill. At the lower end of the line are data for simple airjets; at the upper end of the line are data for engines. The fact that all lie on the same line tells us that the noise producing mechanism is the same for both cases. Since the only noise source for simple airjets is the turbulent mixing process, we know that this must also be the principal noise source for jet engines.

The data in this figure show good agreement for both a 10,000-lb thrust and a 5000-lb thrust engine. The only point off the straight line is for the afterburning case and need not concern us, since afterburning is not currently contemplated for transport airplanes.

Once the noise source is known, it is possible to start seeking ways and means of reducing the noise. If we take another look at the Lighthill parameter we can get some valuable ideas on means of reducing the sound power generated. The atmospheric density  $\rho_0$  and the speed of sound  $a_0$  remain practically constant for any given ground location. The exit area  $A$  is not greatly different for all engines of current interest. The velocity term is the predominant term

in the parameter, since it is raised to the 8th power. Unhappily, most engines in current usage have large values of  $V$ , in the order of 1800 to 2100 ft per sec. The variation of  $V$  between the different engines of 10,000- to 15,000-lb thrust class is small. As a result the sound power generated by all large transport type engines at full power is about the same. One solution to the noise problem was proposed by Silverstein and Sanders at an SAE meeting several years ago. In essence, they proposed that an engine be built which would operate at low jet velocities. They examined a

particular engine design in detail and showed that a low temperature design could be made which would give adequate thrust with fuel economy similar to current engines. Several manufacturers have been working along these lines and this may eventually prove to be an excellent solution. Another engine which also shows low noise level capabilities is the ducted fan or bypass engine, such as the Rolls Royce Conway.

We are faced, however, with the problem that no low noise engine is currently being used in our first series of jet transports. In fact, the

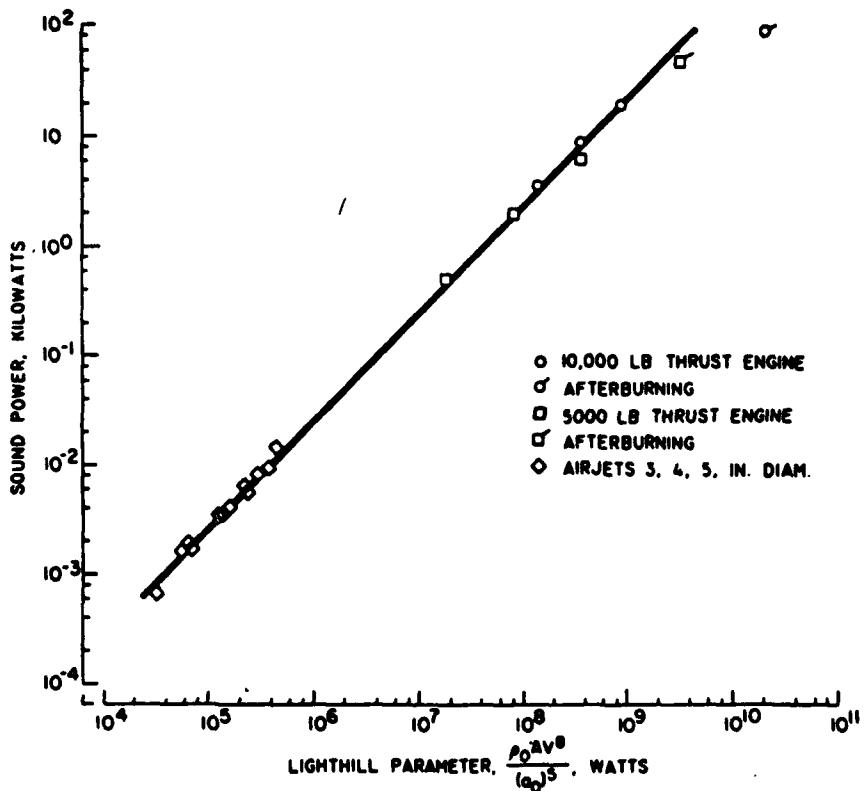


Fig. 2. This plot shows the simple relationship between sound power and the value of the Lighthill parameter that is found experimentally to be valid for a wide variety of circular jets.



Fig. 3. The noise suppressor mounted at the right on this jet engine is a combination of an 8-lobe segmented nozzle and a cylindrical ejector. Acoustical measurements are shown in Fig. 4.

engines which are being used have been developed from high performance military engines. As a result, we have very little control over the engine operation from a noise standpoint. For reasonable aircraft performance, the engines must be operated in a fashion which results in high jet velocities. This then brings us to the real heart of the problem, i.e., how to expand a high velocity jet without at the same time producing the high noise levels which normally accompany such a process. Since the turbulent mixing process downstream of the exit is the noise source we must some-

how alter this process without creating large thrust losses or increases of drag.

You may remember that when we previously examined the Lighthill parameter the predominant term was the velocity since it is raised to the 8th power. In the original theoretical development by Lighthill the velocity used was the local fluctuating turbulent velocity. For all circular jets of reasonable size and velocity the flows are similar. That is if we put the flows on a dimensionless basis by dividing all lengths by the jet diameter and all velocities either mean or fluctuat-

ing by the jet exit velocity then the same general results are obtained. It is only by virtue of the result that all velocities in the jet are proportional to the jet exit velocity that it is possible to substitute the absolute jet velocity for the local fluctuating velocity and obtain the Lighthill parameter previously described. For a jet noise suppressor to work we must change this similarity condition which exists for all circular jets and somehow reduce the fluctuating velocities in our overall jet without any change in the absolute exit velocity of the jet.

A large number of ideas have been presented by many sources. It is difficult to determine sometimes to whom the credit belongs. In general, early workers in the field were Lilley and Greatrex in England, and the staffs of Boeing, Douglas, and Pratt & Whitney, as well as the NACA. The various suppressor nozzles I will discuss represent the ideas of all these groups. All of the data I will present was obtained at NACA Lewis Flight Propulsion Laboratory.

A group of three nozzles which have been rather extensively investigated are shown in the lead photograph. The acoustical characteristics, the internal thrust losses and the external drag have been evaluated. In addition, studies of the turbulence characteristics of similar nozzles have been studied with cold airjet models. The three suppressors shown in the photograph are a corrugated nozzle, open in the center, a corrugated nozzle with a centerbody, and a tubular nozzle. The corrugated nozzles both have twelve separate lobes. The three nozzles shown all obtain their suppression by a similar mechanism. The breaking up of the jet into tubes or slots alters the mixing so that the shear forces are reduced. The outside air which flows in to mix with the jets is speeded up; this reduces the shear and the shears are further reduced by intermixing of the adjacent jets.

Another jet noise suppressor, which is really a combination of a segmented nozzle similar to the one in this photograph and a surrounding cylindrical ejector, is shown

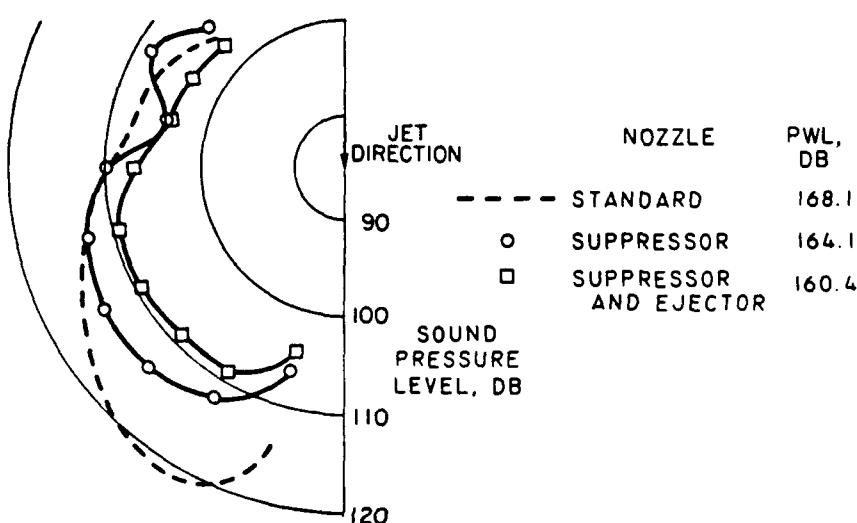


Fig. 4. This plot compares the overall sound pressure levels measured 200 ft from a jet engine with various suppressors. Noise levels are lower at all angles with 8-lobe nozzle and ejector.

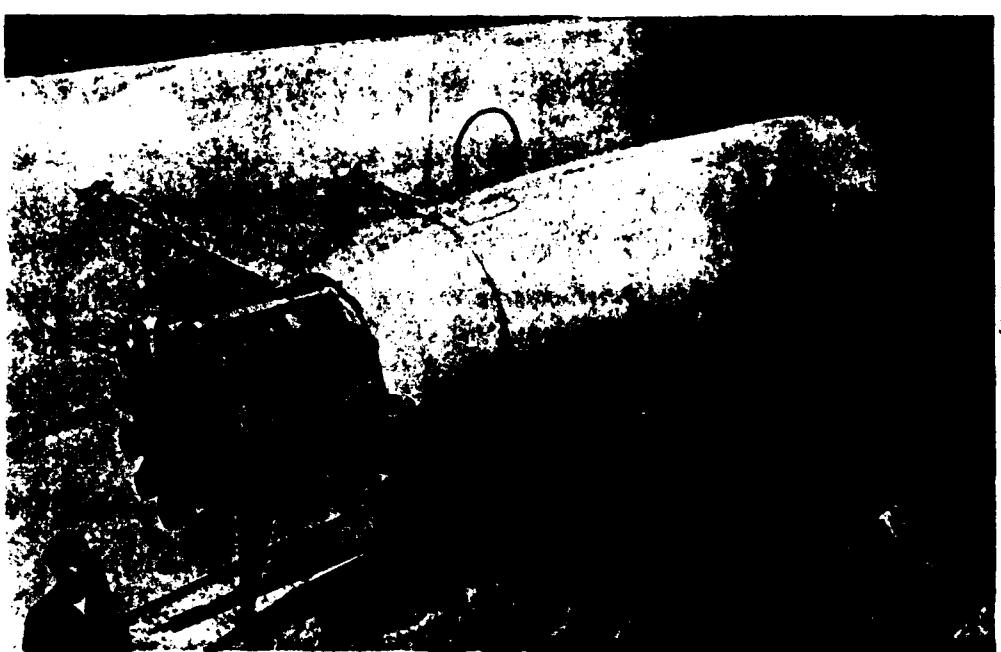
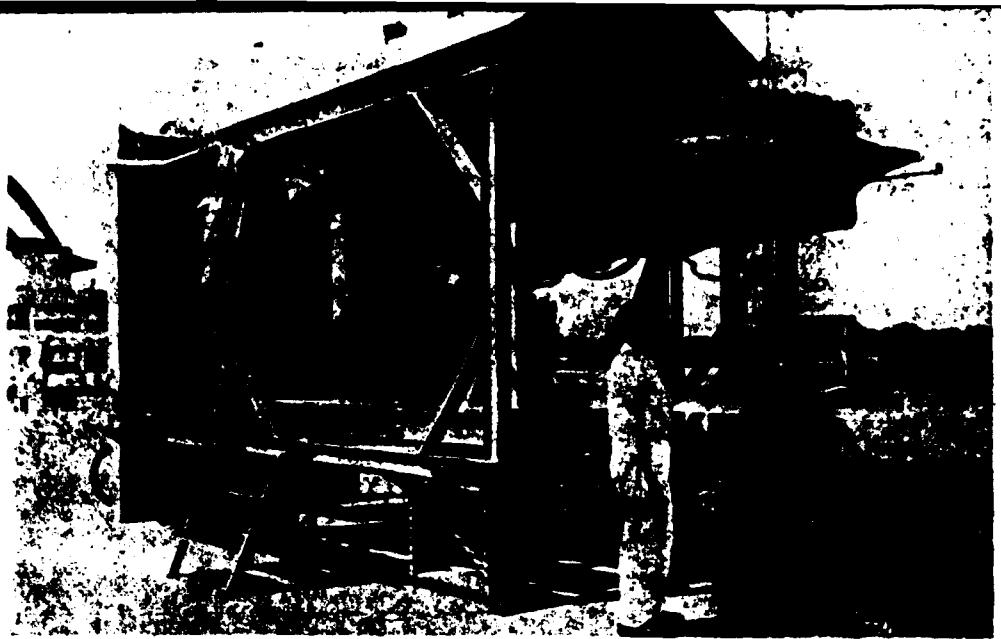
Fig. 5. This 10-slot nozzle is mounted on outdoor thrust stand for test measurements.

Fig. 6. This engine is in a wind tunnel for measuring thrust loss and drag due to nozzle.

Fig. 7. Tests near Mach 1 are made on model suppressors in this transonic wind tunnel.

in Figure 3. This particular suppressor is shown mounted on a B-47 aircraft. The ejector is the cylindrical portion on the rear. The nozzle is an eight-lobed segmented nozzle. The ejector has two functions. It tends to promote more nearly parallel mixing and it provides some thrust augmentation statically and at low forward speeds. It would be expected that such a device would be made to retract forward into the nacelle during cruising flight.

The sound field of this suppressor is shown in Figure 4. Three curves are shown—one for a standard circular nozzle, one for the eight-lobed nozzle without the ejector, and one for the lobed nozzle with ejector. The ejector had an inside diameter 1.6 times the standard nozzle diameter and a length equal to 2.4 times the standard nozzle diameter. The results shown were measured at a distance of 200 ft from the engine exit and at a jet exit velocity of 1700 ft per sec. The circular lines are lines of constant overall sound pressure level. The jet direction is downward on the figure. The maximum noise level of the standard nozzle, i.e., the dashed curve, occurs at about 30° from the jet axis and the value is about 121 db. The lobed nozzle curve shown by the small circles shows a maximum at around 45° of 114 db. It also shows slightly higher values than the standard nozzle up toward the side and front of the engine. Addition of the ejector reduces the noise levels to a maximum of about 109 db and the combination nozzle shows no other peaks. It is quieter everywhere than the standard nozzle. We have tried many combinations of nozzles and ejectors. The best results so far indicate that as much as 15- to 16-db reduction of the maximum overall level is possible. Furthermore, if the ejector is acoustically treated by using a perforated internal wall



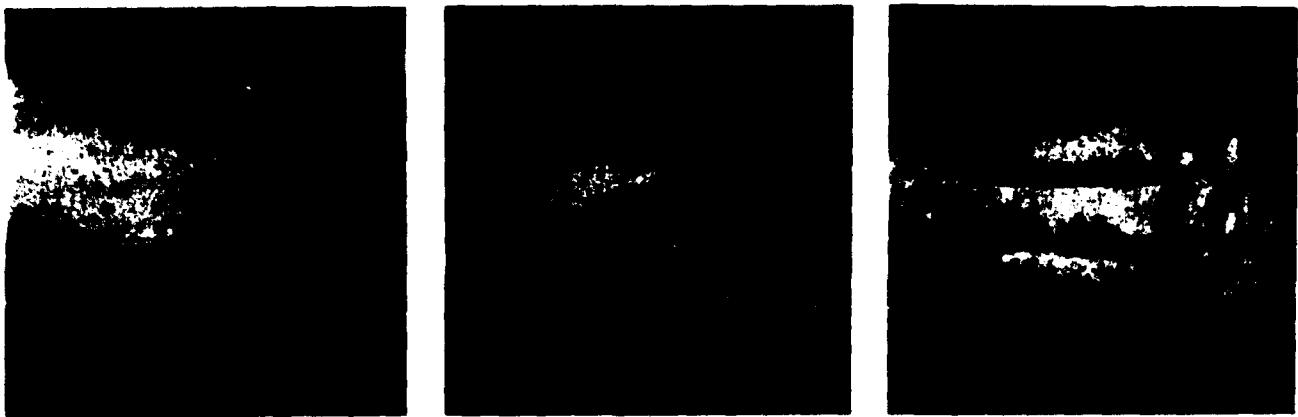


FIG. 8. THIS GROUP OF MODEL SUPPRESSORS WAS TESTED IN THE TRANSONIC WIND TUNNEL FROM MACH 0.6 TO MACH 1.1.

with some absorption material, it is possible to obtain 2- to 3-db more reduction. This results principally from absorption of the higher frequencies. It might be mentioned that these nozzles in general provide about 3 to 4 percent thrust augmentation when tested statically. In general, it would be expected that this augmentation would probably disappear at a few hundred feet per second forward velocity.

It appears to be possible to obtain the reduction of 15 db, which we originally set as our target to make the jet transport operate as quietly as a piston powered aircraft. The question is how much will this cost in aircraft performance. First, from the standpoint of weight, it would appear that if a combination ejector-suppressor nozzle with a built-in thrust reverser is used then it will weigh at least several hundred pounds per engine.

To evaluate the thrust losses and drag penalties we have studied a large number of various types of nozzles in our thrust stands and wind tunnels. Figure 5 shows a thrust stand installation of a parallel slot nozzle. The engine and nozzle characteristics are carefully measured as well as the sound field radiated. This is used as our basic rig for evaluating full-scale nozzles prior to tunnel tests. A great many of the nozzles we tested showed insufficient noise reduction to warrant further work. Furthermore, rigs such as this permit us to work on decreasing internal thrust losses.

Figure 6 shows a photograph of a lobed nozzle mounted in our full-scale altitude wind tunnel. For these tests a 10,000-lb thrust engine was used. The internal thrust losses and external drag can be measured at speeds up to 500 ft per sec and altitudes to 40,000 ft.

Model tests have been conducted in our transonic tunnels to provide additional data since our altitude full-scale tunnel has a quite limited maximum Mach number. The model used to test our nozzles is shown on Figure 7. The nozzles are mounted in the rear. Air for the jet is ducted through wings and expelled. There is no inlet since we wish to study the nozzle performance rather than overall nacelle characteristics. The tunnel walls are perforated to permit transonic flow. The tunnel test section is 8 ft by 6 ft and the model relatively small. This is a requirement necessary for tests at Mach numbers near 1. Figure 8 shows a group of nozzles evaluated over a Mach number range from 0.6 to 1.1. The Reynolds numbers, which are the basis for scaling, are of the same order as for our full-scale studies. Hence, these results should apply directly. All of the nozzles are twin shelled. The thrust forces are measured directly on the inside shell and the drag forces on the outside shell. This technique permits us to find small drag forces which would otherwise be impossible to measure. A number of different nozzles are shown. They are, in general, quite similar to the full-scale nozzles shown previously.

Figure 9 shows a summary of the results obtained from both our model and full-scale tests. The losses in propulsive thrust due to both internal thrust loss and external drag are shown. These data apply for a Mach number of approximately 0.85. This comparison uses the standard nozzle as the zero reference. If we add an ejector to the standard nozzle we suffer a 3.5 percent thrust loss due to drag. The 9-tube nozzle has a 6.5 percent thrust loss caused by a 3 percent drag term and about 4 percent internal losses. The eight-lobed nozzle with centerbody has about a 3.5 percent propulsive thrust loss divided about equally between internal thrust loss and external drag increase. The results for the eight-lobed nozzle with the open center are nearly the same. The combination suppressor using the eight-lobed nozzle with an ejector shows a propulsive thrust loss of about 6.5 percent. This results from a drag term of about 5 percent and an internal thrust loss of 1.5 percent. If the ejector is made retractable then the thrust loss would be that of the nozzle alone, i.e., about 3 percent. From the results shown it is evident that considerable work must be done to clean up the internal and external losses. It should be possible to reduce the overall loss to less than 2 percent without great difficulty by utilizing the knowledge which has been obtained from these and other tests. We know where the losses are and must reduce them.

Before concluding, I would like



NOTE THE DOUBLE-SHELL CONSTRUCTION WHICH MAKES POSSIBLE INDEPENDENT MEASUREMENT OF THRUST AND DRAG FORCES.

to mention that in addition to suppressor nozzles other techniques of noise reduction are also available. North has proposed that the climb-out be initiated at the earliest possible time during the flight. Figure 10 shows the results of his calculations. These calculations apply to a four-engined jet transport aircraft. The abscissa is the horizontal distance from brake release and the ordinate the sound pressure level directly under the aircraft. The absolute levels will vary somewhat dependent on the size and power of the aircraft but the trends of the curves will remain the same. If the aircraft takes off and accelerates at an altitude of 200 ft then the ground levels under the aircraft are high, i.e., of the order of 124 db. If climb is initiated at the earliest possible time, i.e., such that a climb airspeed of 150 knots is used then

the levels drop rapidly and at 3 miles from brake release the level is 104 db at full engine power. These calculations were made assuming no suppressors were used. If a 15 db suppressor is used, then it might be expected that the level would be about 90 db if such a flight technique is employed. The dashed curves show the effects which result from power cutbacks to 80 and 60 percent of available engine thrust. Such procedures are possible, i.e., it is possible to climb at 150 knots at 60 percent engine thrust. However, aircraft safety considerations may obviate such a procedure. The other curves shown indicate what results might be expected from using other climb-out speeds, i.e., 250 knots and 350 knots at various engine powers. It is obvious that such curves only give us certain ground rules

and that individual aircraft, runway orientations, and meteorological conditions will determine which of these flight take-off techniques can be utilized at a given time and for a given location.

For future aircraft there is considerable speculation as to just what the most desirable type of aircraft configuration might be. Certainly we will want to go faster perhaps to Mach numbers of 2 or 3. In addition, we will want relatively short take-off and landing distances. One configuration which is receiving much attention utilizes a great many small engines, perhaps forty or so. These engines would be mounted in the wing and the entire output would be ducted together and out a long narrow slot in the rear of the wing. Such a configuration has been investigated ex-

(Continued on page 80)

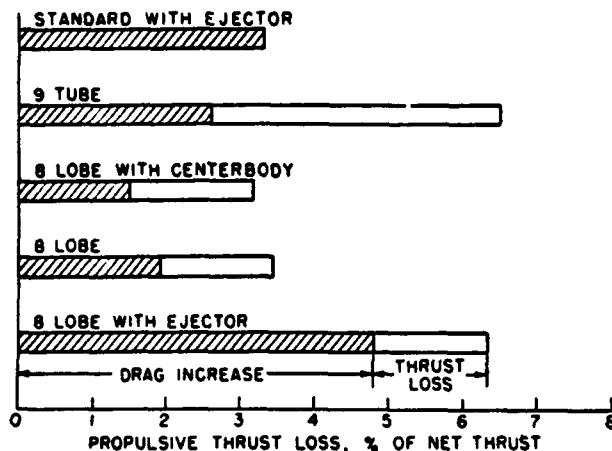


Fig. 9. This chart compares the thrust loss and drag increase, relative to the standard jet nozzle, for the various suppressors.

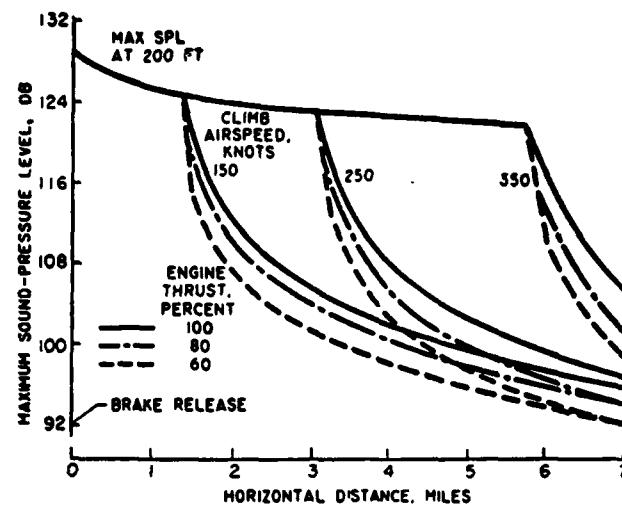


Fig. 10. Flight technique strongly influences the noise at points under flight path. The earlier climb-out is started, the quieter.

## **NOISE SUPPRESSORS FOR JET ENGINES**

*(Continued from page 23)*

perimentally and it appears from our results that very low noise lev-

els can be achieved with such a configuration if proper attention is given to the exit design. Industry is well aware of the noise problem and is taking steps to alleviate it in the early aircraft design stages. It

is hoped, therefore, that future aircraft may present no serious noise problems and perhaps this is one field where no further increases of noise will occur as both the size and power of aircraft go up. ▲▲▲